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FINAL REPORT

TITLE:

PRODUCTION CROSS SECTIONS OF HADRONIC RESONANCES FOR A MONTE CARLO SIMULATION CODE WITH THE EMULSION CHAMBERS

ABSTRACT:

Cross sections to produce hadronic resonances were investigated. Data from proton colliders and electron colliders were surveyed, and appropriate nuclear corrections were made to apply to heavy-ion collisions. A table of cross sections are delivered for Monte Carlo simulation programs. Resonances subjected for this work included σ, ρ, ω, η, ϕ mesons, and Δ baryons. By using the universal parameter of the transverse mass, $m_T \equiv \sqrt{(m^2 + P_T^2)}$, where m and P_T denote meson mass and transverse momentum, respectively, all the resonance cross sections were well approximated by a simple exponential formulae: $E\, d\sigma/dp^3 = \exp(-a\, m_T)$.

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1. Introduction

Observation of low energy or medium-high energy cosmic nuclei can be performed by using electromagnetic interactions only, e.g., magnetic deflection, Cherenkov radiation, transition radiation, and relativistic rise of ionization. However, at high energies above 1,000 GeV/nucleon, most of these methods are not effectively usable, due to the saturation of electromagnetic signals as a fucntion of the velocity (βc), Lorentz Factor (γ), or rigidity (p/Z).

The hadronic cascades in ionization calorimeter or emulsion chambers allow measurements of the energy of primary cosmic rays at high and very high energies by means of hadronic interactions followed by electromagnetic interactions in the detectors. However, it uses the energy transfer of the primary energy into photons via π°-meson production in the initial and secondary hadronic interactions, the knowledge of π°-production is essential for the calorimeter methods. The first approximation can be a use of inclusive cross section of π°-production in proton-proton interactions with suitable corrections on the nuclear effect for nucleus (A) - nucleus (B) collisions. The nucear effect for π-production is known to be approximated by

$$\frac{(dn/dp)_{AB}}{(dn/dp)_{pp}} \approx \frac{(dn/dp)_{AB}}{(dn/dp)_{pA}} \frac{(dn/dp)_{AB}}{(dn/dp)_{pp}} \approx A^{\alpha_1}(p) B^{\alpha\alpha_2}(p)\ \mathrm{f(A,B)}, \tag{1}$$

where

$$\alpha_1 \approx \alpha_2 \approx 0.17 \pm 0.02,$$

$$f(A,B,p) \cong A^{\varepsilon_1} B^{\varepsilon_2} (A^{\lambda_1} + B^{\lambda_2} - C)^{\lambda_0},$$

$$C \approx 0.6 \pm 0.2,$$
$$\varepsilon_1 \approx \varepsilon_2 \approx 0.05 \pm 0.05,$$
$$\lambda_1 \approx \lambda_2 \approx 0.33 \pm 0.05,$$
$$\lambda o \approx 2.00 \pm 0.03.$$

Although the first approximate formulae (1) is satisfactory for most of the Monte Carlo simulations for high energy nuclear cascades in calorimeters, it is often inadequate when the calorimeters measure high P_T cascades, correlations among individual showers, and jet structures. The former, and the latter, too, is subject to the resonance effects. Furtherlomore, open-charm mesons and their resonances have longer lifetimes than that of direct π°-mesons, and their effects on the cascade developments in the calorimeters are energy dependent, particularly, at energy above 100 TeV

Emprical knowledge or theoretical models of the resonance productions are very useful to incorporate these resonance effects for high energy cascade Monte Carlo simulations. We examined various experimental data on pion, kaon and resonance productions from the data bank of proton-proton, proton-nucleus and nucleus-nucleus interactions. By fitting these data to a most simple exponential function, we obtained a satisfactory, approximate, and universal, thermal representation of the resonance cross section.

The first month was devoted to the data collection and archiving. The model comparison with the data was performedin the second month. The third month was used for the test of the parametrized resonance production list with the available heavy-ion data for resonances.

2. Universal Statistical Equilibrium Function

We considered the concept of Hagedorn's statistical bootstrap model as a guideline to find a universal production function of resonances. This is justifiable, because the most of the resonance particle productions in proton-proton interactions have been known to be described by Hagedorn model in terms of

$$d\sigma/dp \approx \exp(-E/T), \tag{2}$$

where E can be approximated by the transverse mass, $m_T \equiv \sqrt{(m^2 + P_T^2)}$, and T is equivalent to the hadronic statistical-equilibrium temperature, To = 176 ± 7 MeV.

Hadronic multiplicity in proton-nucleus and nucleus-nucleus interactions is always higher than that of proton-proton interactions at the same incident energy/n. Likelihood of the statistical hadronic equilibrium is higher in higher multiplicity production processes. Therefore, expectation of the applicability of the Hagedorn concept for nucleus-nucleus interactions is reasonable.

3. Quark Composition and the Mass of Mesons and Resonances

The Quark model is the most successful theory to describe almost all the known mesons and resonances, and it has been considered as the Standard Model for elementary particles and for Quantum-chromo Dynamics (QCD). Table 1 illustrates the quark composition of hadronically-stable, mesons (π's and K's) and baryons (p, n, Λ, Σ's, and Ξ's).

When one quark (or antiquark) is pulled out of the QCD vacuum, a $q\underline{q}$ pair (or more pairs) appears at te breaking point of the "string". The energy of the total system is smaller (until at some point of pair generations) to create a new $q\underline{q}$ pair than to keep storing the potential energy in the string (which is a hadron in the QCD vacuum). In this process of multiple production, it is always more liekly for a pair of $u\underline{u}$ or $d\underline{d}$ to be produced than a pair of $s\underline{s}$ or other massive $q\underline{q}$ ($c\underline{c}$, $b\underline{b}$, and $t\underline{t}$) pair, becasethe higher energy (mass) is required for the latter, and also, because the coupling constant for the latter is weaker. This charateristic nature is consistent with the Hagedon model concept for energetics.

In the production of pions, protons and neutrons (so-called valence quarks) would be the sources for pions in the diffractive (fragmentation) process and/or pionization process (parton recombination):

$$p = duu\ (+\ \text{gluons}) \Rightarrow du - d\underline{d} - u + (\text{gluons}) \Rightarrow d\underline{u} - u\underline{u} - d\underline{d} - u, \tag{3}$$

which is equivalent to:

$$p = duu\ (+\ \text{gluons}) \Rightarrow n\ +\ \pi^{+}\ +\ (\text{gluons}) \Rightarrow p +\ \pi^{-}\ +\ \pi^{+}\ . \qquad (3')$$

Due to the law of Strangeness quantum number conservation, a K^{+} meson ($\underline{s}u$) can only be produced in a pair with other particles that contain s-quark, such as K^{-} ($s\underline{u}$), Λ^{0} or Σ^{0}. This makes an effective reduction of multiplicity of Kaon production at the same available vacuum energy, due to its requirement to be coupled with other massive particles that contain s-quark. This characteristic nature also supports a use of Hagedorn energetics function for kaon productions, too.

$$p = duu\ (+\ \text{gluons}) \Rightarrow du - s\underline{s} - u + (\text{gluons}) \Rightarrow du - u\underline{u} - s\underline{s} - u, \qquad (4)$$

which is equivalent to:

$$p = duu\ (+\ \text{gluons}) \Rightarrow \Lambda^{0}\ (\text{or}\ \Sigma^{0}) +\ K^{+}\ +\ (\text{gluons}) \Rightarrow p +\ K^{-}\ +\ K^{+}\ . \qquad (4')$$

Resonances are essentially higher order SU(3) conbination of quarks, and these fundamental nature would apply: quantum number conservation, and the reduction of multiplicity (cross section) for more massive quark-composition or higher spin particles (also heavier) due to energetics. The Hagedorn exponential function is approximately compatible for both Bose-Einstein particles (mesons) and Fermi-Dirac particles, and therefore, it would hold for any produced particles in any reactions.

Based upon these considerations, we examined the available data and confirmed its validity almost universally in any reactions.

TABLE 1 Quark Composition and Mass of Stable Hadrons (against Hadronic Decays) - Mesons and Baryons

MESONS			**Baryons**		
Species	quark composition	Mass (Mev/c^2)	Specie s	quark composition	Mass (Mev/c^2)
σ^0 (f_0,...) 0^{++}	($u\underline{u}$ +$d\underline{d}$)/√2	~ (600 - 1200)	p	uud	938.27231 ± 0.00028
π^+	$u\underline{d}$	139.5675 ± 0.0004	n	udd	939.56563 ± 0.00028
π^-	$d\underline{u}$	139.5675 ± 0.0004	Λ	uds	1115.63 ± 0.05
π^0	($u\underline{u}$ - $d\underline{d}$)/√2	134.9739 ± 0.0006	Σ^+	uus	1189.37 ± 0.07
K^+	$u\underline{s}$	493.646 ± 0.009	Σ^0	uds	1192.55 ± 0.10
K^-	$\underline{u}s$	493.646 ± 0.009	Σ^-	dds	1197.43 ± 0.06
K^0 (K_L, K_s)	$d\underline{s}$	497.671 ± 0.031	Ξ^0	uss	1314.9 ± 0.6

K^0 (K_L, K_s)	-$\underline{d}$s	497.671 ± 0.031	Ξ^-	dss	1321.32 ± 0.13
η^0	(u$\underline{u}$ + d$\underline{d}$ + s$\underline{s}$)/√3	548.8 ± 0.6	Ω^-	sss	1672.43 ± 0.32

TABLE 2 Quark Composition and the Mass of Major Unstable Resonances - Mesons

$^{2S+1}L_i$	J^{PC}	u$\underline{d}$, u$\underline{u}$, d$\underline{d}$ I = 1	u$\underline{u}$, d$\underline{d}$, s$\underline{s}$ I = 0	c$\underline{c}$ I = 0	b$\underline{b}$ I =1/2	u$\underline{s}$, d$\underline{s}$ I =1/2	$\underline{u}$c, $\underline{d}$c I =1/2	c$\underline{s}$ I = 0	u$\underline{b}$, d$\underline{b}$ I = 1/2
$^1S_0$	0^{-+}	π	η, η'	η_c		K	D	D_s	B
$^3S_1$	1^{--}	ρ	ϕ, ω	J/ψ	υ	K*(892	D* (2010)		
$^1P_1$	1^{+-}	b_1(1235)	h_1 (1170)			K_{1B}	D_1 (2420)	D_{s1}(2536)	
$^3P_0$	0^{++}	a_0 (980)	f_0 (975), f_0 (1400)	χ_{c0} (1P)	χ_{b0} (1P)	K_0* (1430)			

4. Summary of Available Data Status for Resonance Production.

The cross section data of the hadronic resonances are available from the laboratories at DESY, CERN, SLAC, and KEK with electron-positron colliders. Also, data are available from the data bank for the CERN ISR, CERN S(p-bar)-p Collider, FNAL Tevatron and the Particle Data Group at the Stanford University. We got the energy and atomic mass dependences of the cross section from the Brookehaven National Laboratory and CERN heavy-ion experiments.

The updates of the experimental data were comapred with simulation models that include GEAN, Multi-Chain, and a simple quark cascade model. By incorporating the quark and gluon structure functions, we examined the free parameters of the model by fitting to the available experimental data.

Heavy-ion reactions are systematically different from that of elementary reactions, due to the fact that the hydrodynamical flow velocity in heavy-ion reactions cannot be ignored as in small-multiplicity system in elementary particle reactions. In this sense, we examined:

(1) (gluon enhancement parameter) by scaling them to the empirical K/p ratio enhancement factor. to re-adjust the heavy-ion reactions are systematically different from that of elementary reactions.

(2) P_T value re-scaling by reducing the specific flow and obtain the temperature for particle production ratio. The flow velocity was universal to any quarks (light or heavy),

and the apparent P_T is enhanced for heavy quark mesons and baryons, due to its flow energy.

Particular attention were paid about the strange mesons. K-mesons and f mesons were enhanced in heavy ion collisions, and their enhancement factors in P_T cannot be derived straightforwardly from the data in elementary particle reactions and Hagedorn exponential thermal function, because heavy-ion collisions include an influence of hydrodynamical flow of quarks in many-body ststem. Fig. 3 shows the adjustment required in m_T and P_T to use the exponential function. Using the corrected m_T by reducing the flow component in P_T, that corresponds to the value shown in Table. 3, the particle production cross section as a function of m_T (less flow) can satisfactorily preserve the validity of the universal exponential function for particle production.

Model	A (A*)	B	C
T (MeV)	232	150	190
β_f	0	0.41	0.20
λ_q	1.49 ± 0.05	1.48 ± 0.05	1.48 ± 0.05
λ_s	1.03 ± 0.05	1.03 ± 0.05	1.03 ± 0.05
γ_s	0.69 ± 0.06	0.79 ± 0.06	0.68 ± 0.06
μ_B (MeV)	280 ± 20	175 ± 15	220 ± 20
μ_s (MeV)	7 ± 11	4 ± 7	5.5 ± 9
S/B	18.5 ± 1.5 (22.5 ± 2)	48 ± 5	26 ± 2.5
D_Q	0.135 ± 0.001 (0.11 ± 0.01)	0.08 ± 0.01	0.12 ± 0.01
K^-/K^+	0.53 ± 0.08	0.51 ± 0.08	0.53 ± 0.08
$\bar{p}/p$	0.10 ± 0.02	0.10 ± 0.02	0.10 ± 0.02
$\bar{\Omega}/\Omega$	0.85 ± 0.25	0.85 ± 0.25	0.85 ± 0.25
Λ/p	0.60 ± 0.06	0.62 ± 0.06	0.59 ± 0.06
$\bar{\Lambda}/\bar{p}$	1.2 ± 0.01	1.2 ± 0.01	1.2 ± 0.01
Ω^-/Ξ^-	0.53 ± 0.05	0.29 ± 0.03	0.45 ± 0.04
$\bar{\Omega}^+/\bar{\Xi}^+$	1.1 ± 0.1	0.60 ± 0.06	0.94 ± 0.09

Table 3: Thermal fireball parameters extracted from the WA85 data [ ] on strange baryon and anti-baryon production (see text), and some predicted particle ratios in the same kinematic region based on these parameters. The hadron gas models A, B, and C differ by the choice of the pairs (T, β_f) as given in the table, all yielding the same $m_\perp$-slope. The model A* breaks chemical equilibrium by assuming that all baryons are suppressed relative to all mesons by a coalescence penalty factor $C_B/C_M = 0.625$. This renders the hadronic system A* strangeness neutral.

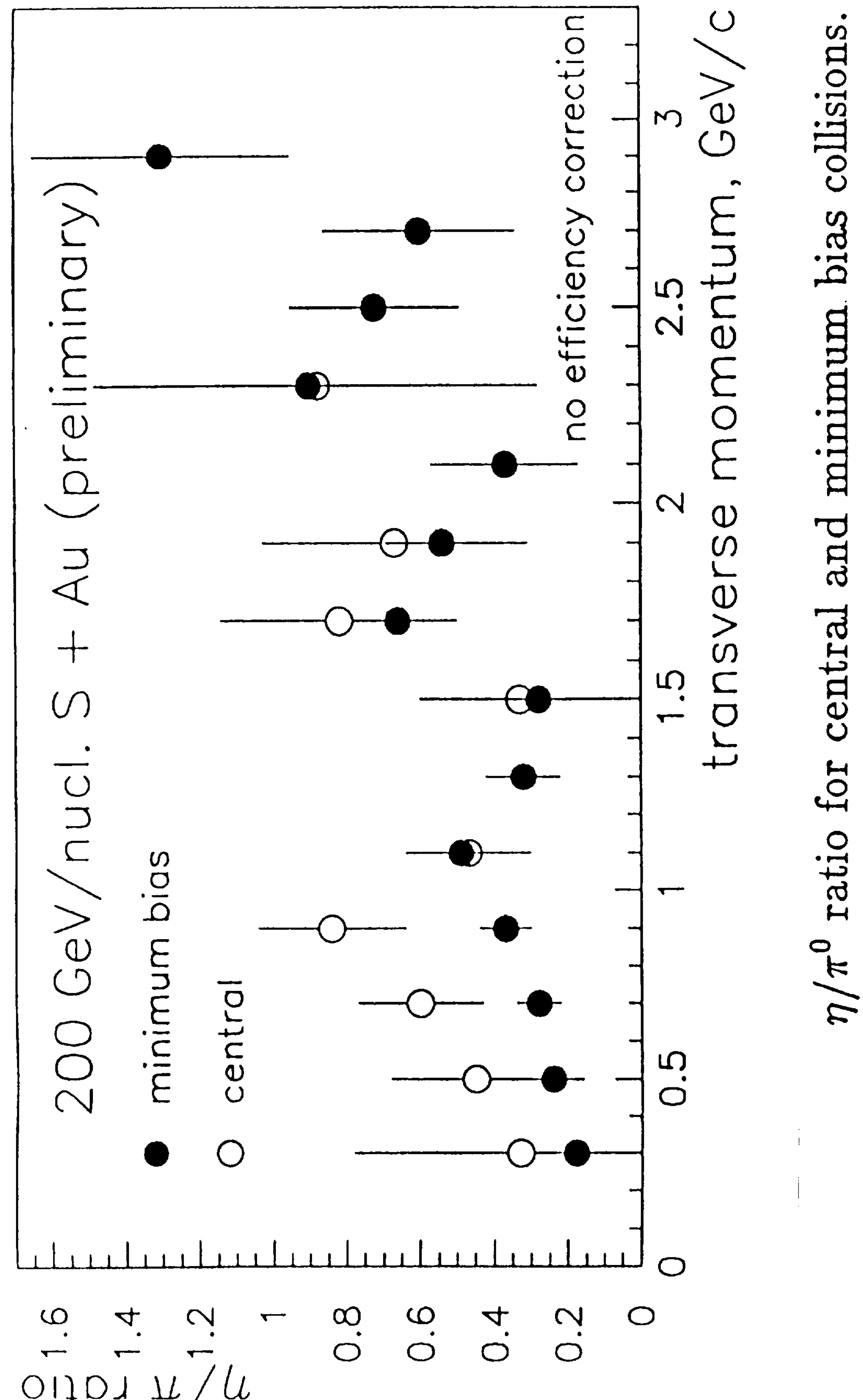
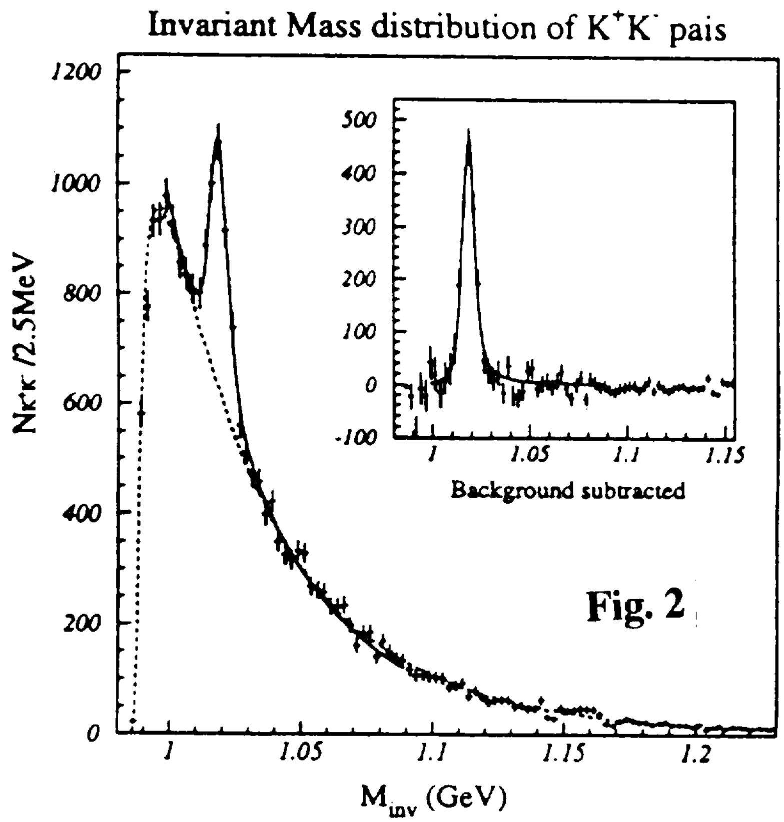


FIG. 1 η-PRODUCTION.



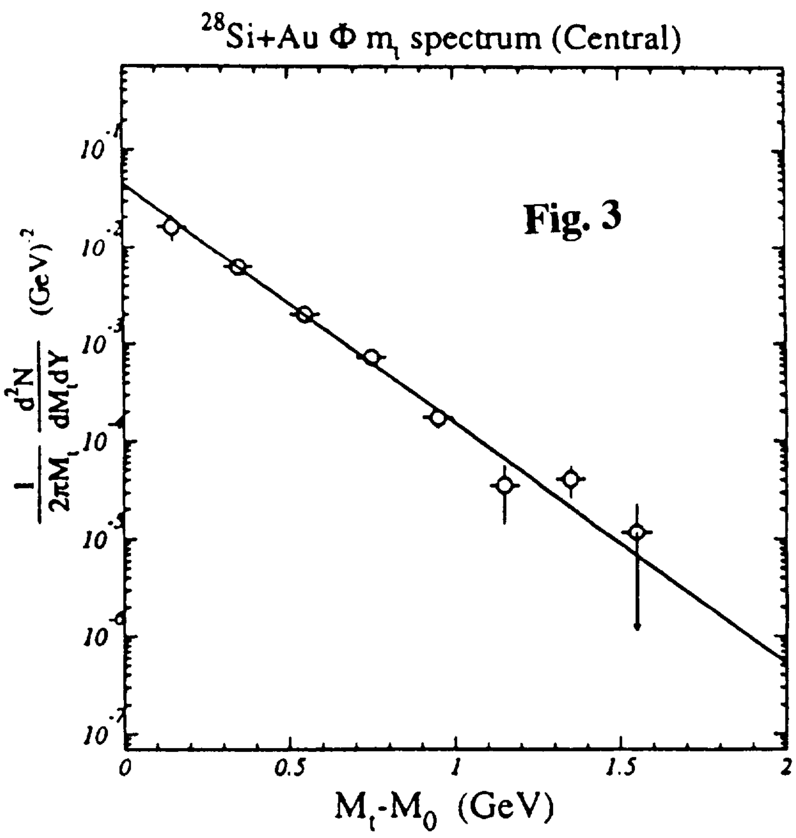


Fig. 2, Fig. 3 ϕ-meson production

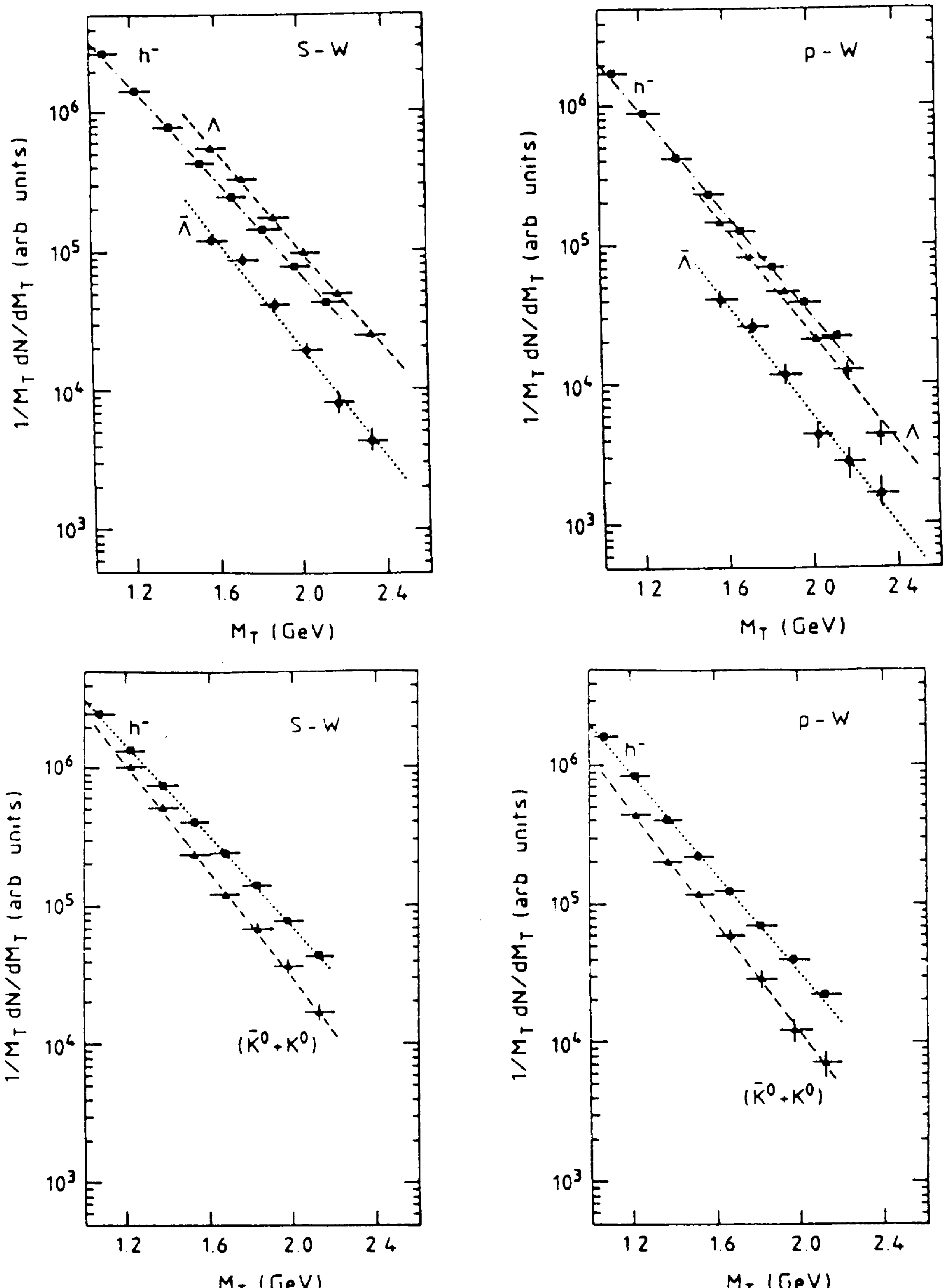


Fig. 4. Hyperon Production

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